

Synchronized Switch Harvesting Technique Applied to Electromagnetic Vibrations Harvester

E. Arroyo*, A. Badel, F. Formosa
 SYMME, Université de Savoie, Annecy, France

Abstract: This paper presents the study of a new application of non linear techniques for energy harvesting. The Synchronous Electric Charge Extraction (SECE) harvesting technique for piezoelectric generators is extended and adapted to electromagnetic generators. Because of the magnetic flux/electrical charge duality, this new circuit is named SMFE for Synchronous Magnetic Flux Extraction. A global theoretical model is developed, and harvested power is simulated. Comparisons with a standard impedance matching extraction technique show that over twice the power can be harvested in a restricted area of the characteristic parameters. It also allows the maximum power to be harvested whatever the load value is, whereas impedance matching technique needs a constant tuning which is practically difficult to implement with a self supplied electronic. Finally, in order to confirm the theoretical results, the SMFE circuit was embedded and tested on a simple centimeter-scale electromagnetic harvester.

Keywords: vibrations harvester, electromagnetic generator, energy conversion, non linear technique

INTRODUCTION

Over recent years has been an increasing interest in wireless sensors networks. Harvesting power from ambient vibrations appears to be a great way to supply these low-power consumption systems. Piezoelectric harvesting generators have been widely studied [1], and non linear methods of energy extraction have been developed in order to optimize their performances [2]. For instance, Lefeuvre et al [3] showed that Synchronous Electric Charge Extraction (SECE) for a piezoelectric harvester could greatly enhance the electromechanical conversion while tackling impedance matching issue. There are also works on electromagnetic harvesters [4], but few of them are considering non linear extraction of energy: Lallart and all [5] extended the non linear energy extraction strategy to electromagnetic systems. They considered the control of the magnetic induced current supplied by an electromagnetic generator, thus implying a possible extension of SECE to electromagnetic generators. However in this theoretical study, resistive losses were not taken into account, which appears to be a strong limitation in the case of a wounded coil-magnet system.

Following these studies, the present paper investigates the SECE method applied to electromagnetic harvesters. Because of the magnetic flux/ electrical charge duality, this method is named Synchronous Magnetic Flux Extraction (SMFE). In the first section, a global theoretical model of a classical electromagnetic generator is developed. This model takes into account both the inductance and the resistance of the coil. In the second section, the SMFE technique is simulated. Results are analyzed and compared with the classical model performances. Finally, the SMFE technique was performed on an experimental setup made of a shaker and a simple meso-scale electromagnetic generator.

THEORETICAL MODEL

Most electromagnetic inertial generators vibrate at a resonance frequency and can be modeled as a second order mass-spring-damper system constituted by a coil tied to a spring and set into the magnetic field of a permanent magnet (Fig. 1). The relative motion between the coil and the magnet, created by the external vibrations, induces a voltage at the coil terminals. The input force is represented as F . For the classical inertial generators $F=M\gamma$ with γ the acceleration of the frame. The damping coefficient C embodies the mechanical parasitic losses.

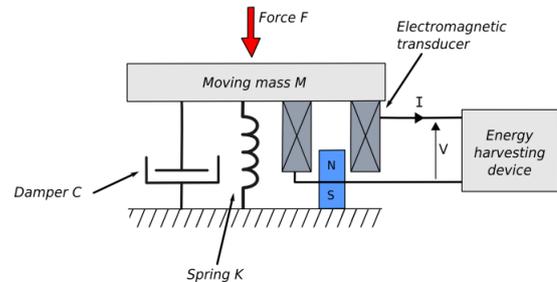


Fig. 1: Model of an electromagnetic inertial generator.

The electromagnetic generator behaves as a voltage source whose value is proportional to the mass velocity, in series with the coil inductance and resistance. Both the inductance and the resistance of the coil are taken into account in the model. Assuming that a harmonic force of constant magnitude is applied, and that the frequency of vibration is close to the resonance frequency of the generator, its behavior is described by the following coupled mechanical and electrical equations:

$$F = M\ddot{u} + C\dot{u} + Ku + \beta I \quad (1)$$

$$V = \beta\dot{u} - r_L I - L_0 \dot{I} \quad (2)$$

Five parameters are introduced in order to conduct the study with normalized equations:

Parameter	Symbol	Value
Squared coupling coefficient	k^2	$\frac{\beta^2}{KL_0}$
Mechanical quality factor	Q_m	$\frac{\sqrt{KM}}{C}$
Resonance angular frequency	ω_0	$\sqrt{K/M}$
Load coefficient	ξ_c	$\frac{R}{2L_0\omega_0}$
Resistance losses coefficient	ξ_e	$\frac{r_L}{2L_0\omega_0}$

Table 1: Parameters introduced for the study.

Electromagnetic harvester with classical extraction technique

Classic energy extraction circuits use an association of an AC/DC and a DC/DC converter to charge the storage element. A simplified and usual view consists in a resistive load connected to the generator, which value is adapted to harvest the maximum power (Fig. 2). This is the circuit considered in this study. This approach represents a theoretical and better case than what is actually put on a harvester.

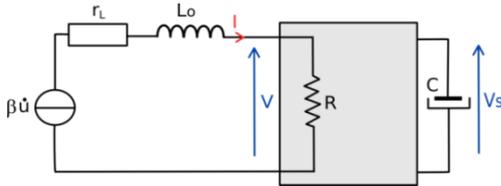


Fig. 2: Classical matching impedance circuit.

The power dissipated within the load resistance is calculated from Eq. 1 and 2. Its expression is given by Eq. 3, as a function of the parameters in Table 1.

$$P_R = RI^2 = \frac{k^2 \xi_c}{[1+4(\xi_e+\xi_c)^2] + \left[\frac{1}{2Q_m} + \frac{k^2(\xi_e+\xi_c)}{1+4(\xi_e+\xi_c)^2}\right]^2 4\omega_0} \gamma^2 M \quad (3)$$

This power depends on the electrical load value represented as ξ_c . Numerical simulations show that this power reaches two maxima when $\xi_e = 0$. If $\xi_e > 0$, there is only one maximum value for one optimal load depending on k^2 (Fig. 3). As k^2 is increasing, the harvested power tends towards a limit power (P_{LIM}), which is a function of the mass acceleration M , the quality factor Q_m , and the resonance frequency ω_0 :

$$P_{LIM} = \frac{\gamma^2 M Q_m}{4\omega_0} \quad (4)$$

A Normalized power is then defined as:

$$\frac{P}{P_{LIM}} = \frac{P_R}{P_{LIM}} \quad (5)$$

Assuming that the impedance is always adapted to fit the best case, the normalized power can be plotted as a function of the product $k^2 \cdot Q_m$, and the losses

coefficient ξ_e (Fig. 4). The power is all the more reduced that the losses coefficient is important.

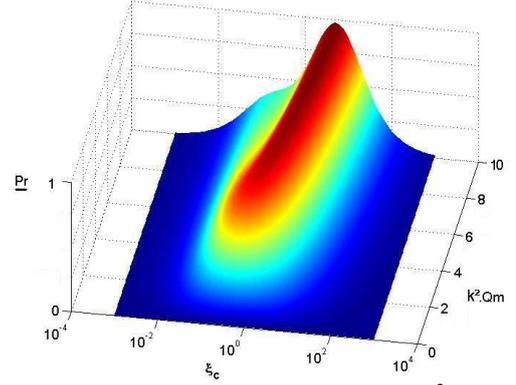


Fig. 3: Harvested power versus load and $k^2 \cdot Q_m$ for $\xi_e = 0.01$.

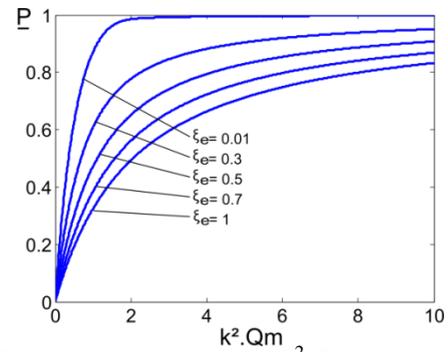


Fig. 4: Harvested power versus $k^2 \cdot Q_m$.

Electromagnetic harvester with SMFE technique

Continuous impedance matching strategy implies a continuous tuning of the converter, which is actually difficult to be carried out with a self-powered electronic. It has been shown that using non linear techniques to extract the energy from piezoelectric elements is a solution to get rid of this issue. In particular, the SECE technique appears to be competitive considering the power extracted, while allowing the maximum energy to be transferred to the load, whatever its value is. The SECE technique consists in switching the piezoelectric element on a coil during a short time at each extremum of the displacement. A schematic of the circuit is presented Fig. 5. The electrical energy stored on the piezoelectric element capacitor is transferred to the inductance L when the switch is closed. When all the electrical charges are transferred, the switch is opened again and the inductance discharges in the capacitive storage which supplies a load R .

Based on the same principle, the SMFE technique has been developed for electromagnetic generators: its principle is to switch the electromagnetic element on a storage capacitor at each extremum of the magnetic induced current. As the electromagnetic transducer is a current source, this technique does not require an intermediate level of conversion and energy can theoretically be directly transferred from the coil to the storage element. Fig.6 presents a schematic of the circuit.

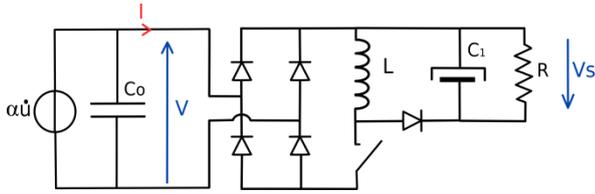


Fig. 5: SECE circuit.

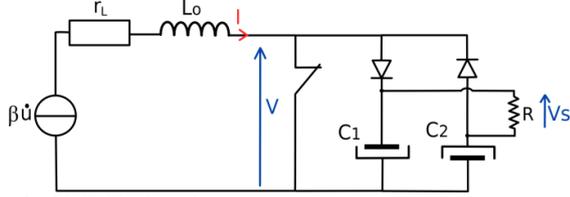


Fig. 6: SMFE circuit.

The electromagnetic induced current can be written as a function of parameters defined in Table 1, and other parameters depending on the commutation like ψ which is the phase angle introduced by the R_L , L_0 dipole and Φ which is the phase angle between a maximum of displacement and the time of commutation. Φ is deduced from the current expression, as the value that maximizes the current at each commutation, two times in a period.

$$\phi = \arctan\left(\frac{4\xi_e}{1-4\xi_e^2}\right) \quad (6)$$

$$\psi = \arctan\left(\frac{1}{2\xi_e}\right) \quad (7)$$

The current expression is developed in Fourier series and the first harmonic approximation is applied in order to calculate the displacement of the mass. Assuming that the energy transferred to the capacitor at each period is equal to the energy stored in the inductance, the expression of the harvested power is given in Eq. 8 as a function of the displacement magnitude (Eq. 9, 10).

$$P_{SMFE} = \frac{k^2 \omega_0^3 M \sin^2(\phi + \psi) (1 - e^{-2\pi\xi_e})^2}{2\pi(4\xi_e^2 + 1)} u_M^2 \quad (8)$$

$$u_M^2 = \frac{\gamma^2 / \omega_0^4}{[\frac{\alpha}{2} \sin(2\phi + 2\psi)]^2 + [\frac{1}{Q_m} + \alpha \sin^2(\psi + \phi)]^2} \quad (9)$$

$$\alpha = \frac{2k^2(1 + e^{-2\pi\xi_e})}{\pi(1 + 4\xi_e^2)} \quad (10)$$

This power does not depend on the load coefficient ξ_c any more. Thus its evolution will be studied as a function of $k^2.Q_m$ and ξ_e , and compared with the classical technique.

SIMULATION RESULTS

Numerical simulations have been performed to compare the normalized power extracted with the SMFE circuit (\underline{P}_{SMFE}) to the maximum power harvested with the standard technique with matching impedance (\underline{P}_R).

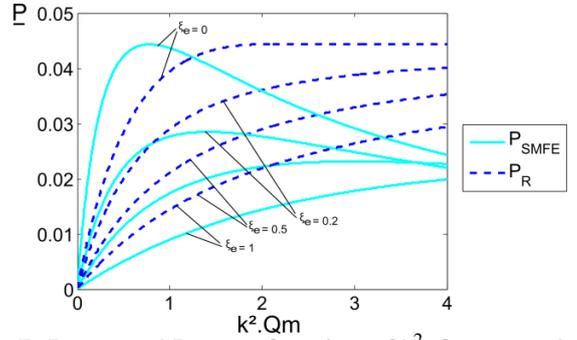


Fig. 7: \underline{P}_{SMFE} and \underline{P}_R as a function of k^2 , for several ξ_e .

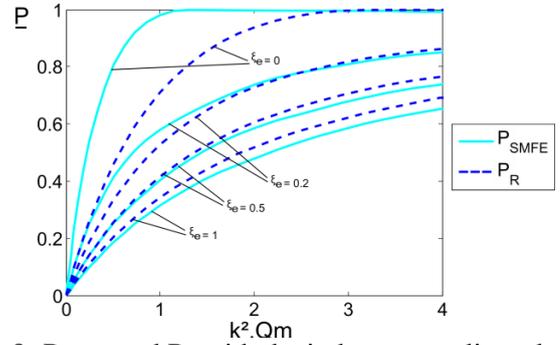


Fig. 8: \underline{P}_{SMFE} and \underline{P}_R with the inductance adjusted.

Fig. 7 shows \underline{P}_{SMFE} and \underline{P}_R as a function of $k^2.Q_m$ and for several values of ξ_e . According to this plot, for small values of $k^2.Q_m$ the SMFE technique allows up to 2.5 more power as the classical technique to be extracted. Therefore it leads to extract the same or more power for less electromechanical coupling. When $k^2.Q_m$ increases, the damping induced by the energy harvesting becomes too important and induces a decrease of the extracted power.

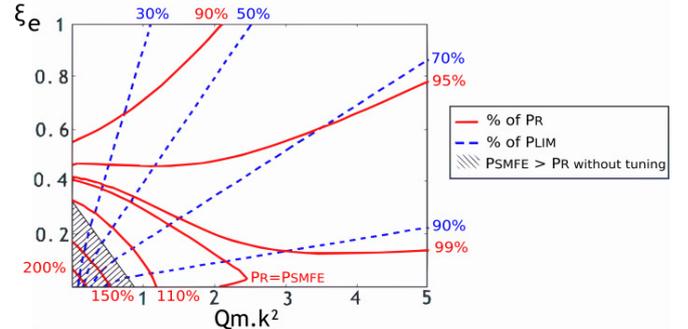


Fig. 9: \underline{P}_{SMFE} compared with \underline{P}_R as a function of specified $k^2.Q_m$, and ξ_e parameters values.

Noted that ξ_e and k^2 are both inversely proportional to the coil inductance L_0 , it is possible to adjust their value by modifying the inductance of the generator. This can be simply done, either by optimizing the electromagnetic circuit geometry, or by adding a coil in series with the generator. This tuning enables the generator to harvest the maximal power whatever the initial coupling of the system is. Fig. 8 shows the harvested power with the best inductance setting, as a function of the initial coupling coefficient and initial losses parameter. Fig. 9 sums up the results and shows the areas of the plan ($k^2.Q_m$, ξ_e) with the denoted level of power harvested. Considering a generator with

specified k^2 , ξ_e and Q_m parameters values, this graph shows how profitable it is to use the SMFE technique. The hatched area corresponds to the best case: without any inductance tuning, the SMFE technique would allow up to 2.5 more power to be harvested.

EXPERIMENTAL RESULTS

The SMFE technique was tested on a non-optimized centimeter-scale electromagnetic generator. It is put on a shaker and the coil terminals are connected either to the classical, or to the SMFE circuit. Measures are done at 153Hz (resonance frequency of the system), for an acceleration of a few g. The generator parameters are $k^2=0.30\%$, $\xi_e=1.0$, $Q_m=50$.

The power extracted with the classical technique strongly depends on the load value. If the resistance is directly connected to the generator, the power reaches a maximum of 3.04mW for a resistance of 2Ω but it drops below 1mW for resistances lower than 0.25Ω and higher than 20Ω . AC voltages of around 0.1mV are measured. As DC voltages are required in most applications, a rectifier has to be added to the circuit. When using a classical 4 diodes bridge, the extracted power cuts down under 0.1mW because of the voltage drop due to the diodes threshold voltage.

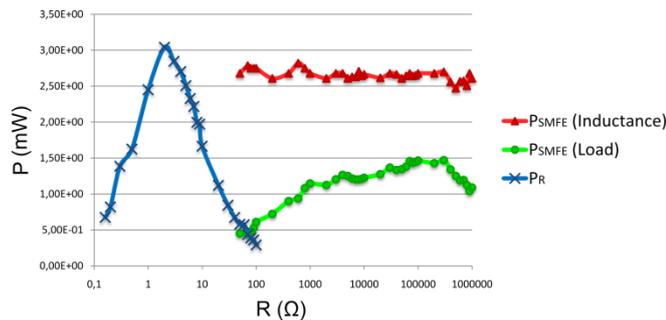


Fig. 10: Experimental results: Power with the classical technique (P_R), P_{SMFE} deduced from the current measured in the inductance ($P_{SMFE(inductance)}=Li_L^2f$), and P_{SMFE} measured at the load.

With the SMFE circuit, an inductance of 1mH is added in series with the generator. The current in the coil is reduced to zero two times a period when the switch allows the charge of C_1 or C_2 , as shown in Fig.11. To compare the experimental results with the theoretical simulations, the extracted power is deduced from the energy stored in the inductance during two periods of time. As expected, it remains constant (around 2,7mW) whatever the load value. Regarding the power dissipated at the load resistance, it is approximately constant from $1k\Omega$ and beyond (Fig.10). For smaller load values the power decreases because of the increasing effect of the diodes threshold voltage. The difference between the power extracted by the inductance and dissipated the load is due to the resistive losses and the diodes threshold voltage. It could be reduced by optimizing the circuit components and by reducing the resistive effects.

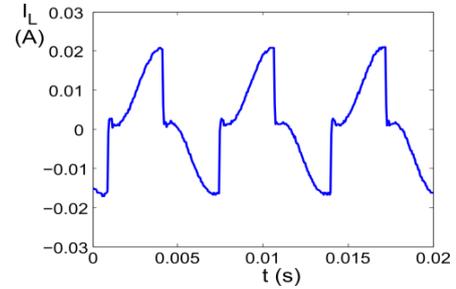


Fig. 11: Experimental current waveform.

These results are in agreement with the theoretical simulations: Fig. 9 shows that due to the unfavorable generator parameters, P_{SMFE} is about 90% of P_R . However, practically the SMFE technique allows supplying usable DC voltages [1V to 30V] whatever the load is, whereas the power harvested by the classical technique can't be directly nor simply used.

CONCLUSION

A complete model of an electromagnetic inertial generator has been developed. A classical extraction technique has been compared theoretically to the new non linear technique (SMFE). Simulation results showed that the SMFE technique efficiently addresses the impedance matching issue observed using the classical approach and that it can improve the maximal harvested power for low resistive losses and low coupling generators. Experiments on a generator pointed out that the dependence on the load is strongly reduced, and that a usable continuous voltage is delivered to the load. An optimized generator is under development, which should allow a study of the SMFE technique under optimal conditions.

REFERENCES

- [1] Anton S.R., Sodano H.A, 2007 A Review of Power Harvesting using Piezoelectric Materials (2003–2006). *Smart Materials and Structures*, **16(3)**, 1-21.
- [2] Badel A, Guyomar D, Lefeuvre E, Richard C, 2006 Piezoelectric energy harvesting using a synchronized switch technique. *Journal of intelligent Material Systems and Structures*, 17(8-9): 831-839
- [3] Lefeuvre E, Badel A, Richard C, Guyomar D 2005, Piezoelectric energy harvesting device optimization by synchronous electric charge extraction, *Journal of Intelligent Material Systems and Structures*, **16(10)** 7-18.
- [4] Von Büren T, Tröster G, 2007, Design and optimization of a linear vibration-driven electromagnetic micro-power generator, *Sensors and Actuators A: Physical*, **135**, 765-775 .
- [5] Lallart M, Magnet C, Richard C, Lefeuvre E, Petit L, Guyomar D, Bouillault F, 2008, New synchronized switch damping methods using dual transformations, *Sensors and Actuators A: Physical*, **143(2)**, 302-314.